

Original Articles

Coastal systems in transition: The game of possibilities for sustainability under global climate change

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ABSTRACT

To achieve ecological sustainability and sustainable development represents a crucial challenge for the human kind, which depends on numerous driving forces, frequently opposing each other. Nevertheless, when dealing for instance with estuaries and coastal areas, three major drivers may in any case be identified, which are the search for human well-being in its several aspects, the conservation of environmental equilibrium, essential to ecological sustainability, and systems' resilience in face of an increasing human pressure, resulting from population size and prosperity demand.

To build and test environmental management scenarios involves therefore complex conceptual problems, demanding appropriate conceptual tools as for example the Ecological Sustainability Trigon (EST). Conceptually, the EST allows addressing the referred main drivers by using the human society view as a common currency, and to describe our behavior, energetics (economy), and dynamics based on ecological theory. Besides, the EST behaves promisingly as a gap analysis tool and a mean to address new research questions. Since its proposal, the EST has been further tested, namely in relation to the functioning and management of estuarine ecosystems and coastal areas, taking the Mondego Estuary (western Portugal) as core case study.

1. Introduction

Among all types of environments worldwide, estuaries and coastal areas are particularly threatened as a consequence of pollution, over exploitation, and impacts of climate change, which increased awareness of the intense impact of humans on ecosystems functioning. As a consequence, there is a well identified need for approaches to sustain and where necessary restore such ecosystems (Hughes et al., 2005). Approximately 25 years ago the idea of *sustainable development* emerged (Pulselli et al., 2008), but there is no agreement regarding the precise understanding and definition of the term among researchers from different disciplines. "Development that satisfies present needs without compromising the possibility of future generations satisfying theirs" (Brundtland, 1987) is probably the most commonly adopted definition of sustainable development, but this definition is relatively vague and non-operational. In fact, to apply the concept, additional quantification from the scientific, cultural, and socio-economic points of view is required, and besides it is necessary to take into account time, relationships, and biophysical limits (Pulselli et al., 2008).

More often, the human society does not evolve in harmony with environment's capability to produce the assets necessary for its development, which turns time a very important factor with regard to sustainability. But despite the fact that sustainable development became a

crucial challenge, the way human society interacts with the various needed living and non-living natural resources, which constitute what is called natural capital, is still controversial, to say the least. Essentially, there are two main indubitably contrary perspectives regarding the conceivable practical mean of sustainability: weak and strong sustainability. Weak sustainability admits that human well-being must continue through intergenerational time scales, considering that natural capital and man-made capital can be inter-converted in the scope of specific production processes (Brand, 2009). Consequently, weak sustainability also accepts the option of depleting natural capital, unless its requirement tends to decline over time (Brand, 2009). Inversely, strong sustainability takes up a complementarity between natural capital and man-made capital, assuming that the whole stock of natural capital has to be preserved for present and future generations in the long run, and therefore that human society must keep each type of capital intact over time (Brand, 2009). Despite these conflicting perspectives, the fact that humans and their cultural diversity are recognized as an integral component of ecosystems, and awareness concerning predictable hazards arising from a serious worldwide environmental degradation, forced the entrance of ecological sustainability into international agendas.

Regardless from the conceptual approach adopted, resilience, the capacity to cope and adapt, and the conservation of sources of

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innovation and renewal constitute critical factors for sustainability when uncertainties and change are key questions of environmental and social organization (Lebel et al., 2006). Consequently, the sustainable management of natural systems implies attaining steadiness between delivering those economic goods and services provided by the environment, indispensable for societal health and functioning, and simultaneously continue and preserve ecological goods and services essential for natural systems health and functioning (Mitsch and Jørgensen, 2003).

The maintenance of environment and natural resources might be irreconcilable with our present economical paradigm, and therefore relationships become a crucial concern. Indeed, efficient allocation of resources is often not taken into account by economic instruments, which tend to consider only issues directly driven by the market (Pulselli et al., 2008), while relationships imply interdependencies and consequently the need to determine at what scale (regional, national, etc.) different aspects are interdependent.

Finally, at each place, human populations cannot easily fulfil their needs in terms of materials, energy, land, waste sinks and information proceeding from local resources and therefore biophysical limits must be taken into account. The concept of “critical natural capital”, developed between the “weak” and “strong” sustainability perspectives, reflects this evident fact. Critical natural capital may then be seen as the part of the natural capital that perform significant and unique environmental functions, ensuring therefore ecosystem services that cannot be replaced by other types of capital (de Groot et al., 2003). Actually, especially in recent centuries, societal development has been driven mostly by finite, non-renewable resources, and such perception conveyed the general acceptance that the maintenance of critical natural capital is required in order to attain environmental sustainability and sustainable development (Ekins et al., 2003; Mitsch and Jørgensen, 2004).

The evaluation of natural capital is required in at least six domains: socio-cultural, ecological, sustainability, ethical, economic and human survival (Brand, 2009). Besides, sustainable environmental management can only be attained if options and actions undertaken are environmentally and ecologically sustainable, economically realistic, technologically feasible, socially desirable or at least socially tolerable, administratively manageable, legally admissible and politically opportune (e.g. Elliott et al., 2006; Bunce et al., 2008; Mee et al., 2008; Ojeda-Martínez et al., 2009). These are the essential conditions to achieve the main challenge for natural and social sciences, which is presently the maintenance or even the increase of economic goods and services demanded by a developing society and simultaneously maintaining and protecting ecological goods and services; these together represent environmental goods and services.

Natural and social aspects of ecosystems are intimately linked, which is reflected in “The Ecosystem Approach” in strict sense (e.g. Convention for Biological Diversity; Kay et al., 1999). For instance, environmental restoration, crucial in now days, involves dealing with complex problems like a) losses of species diversity, habitats, and a reduction in habitats heterogeneity and size, b) changes in dynamics and spatial distribution of many species, as well as diminution of their populations size, c) fragmentation of habitats and associated increase in the vulnerability of the remaining isolated patches, and d) reduction of economically significant services and goods naturally offered by ecosystems (e.g. Elliott et al., 2007).

The challenge of seeking for ecological sustainability must be met within this framework, in which some ecological concepts are well understood or at least appropriately defined, like for instance the nature of ecosystem structure and functioning, whereas others, like resilience, carrying capacity, or ecosystem goods and services are not yet adequately quantified.

At present, from the ecological point of view, health of ecosystems is often assessed based on the abundances of few conspicuous (or even charismatic) species, namely birds, fishes and marine mammals.

Weaknesses of such approach are manifest because the mechanisms underlying temporal or spatial variations in abundance are frequently poorly understood and the way changes in these species influence ecosystems as a whole are rarely addressed (Hughes et al., 2005). Resilience-based management, for example, constitutes therefore an innovative and appropriate approach to marine and coastal ecosystems, especially if applied to fisheries, providing a shift in focus from the conservation of targeted species, frequently commercially important ones, to the active management of functional groups supporting critical processes and the maintenance of ecosystems services (Hughes et al., 2005). This focus on functional groups assumes the importance of species interactions and ecological roles (including that of humans) in sustaining ecosystems resilience through spatial and temporal scales, representing a clear change in perspective (Folke, 2006).

The resilience concept, despite its central position in sustainability science, has been suffering significant changes through the last three decades (Walker et al., 2004). In fact, there are confusions around the term, and several attempts have been undertaken to clarify it (Elliott et al., 2007), assuming the perspective that it refers to the intrinsic capacity of a system of coming back to a prior or similar state after a disturbance. Additionally, Elliott et al. (2007) specified that resistance is the capacity of the system to tolerate stressors. Yet, there are at least two other meanings which can be found in the literature. One refers to the dynamics of close to equilibrium systems, being defined as the time necessary to their return to an equilibrium point after a disturbance, addressing therefore systems recovery. This is commonly called “engineering resilience” (Holling, 1996; Folke, 2006), being in a large extent equivalent to the stability property “elasticity” (Grimm and Wissel, 1997), or “resistance to change” (Levin and Lubchenco, 2008). A second one is defined as the capacity to absorb stress and still maintain “function”, referring to the dynamics of far from any equilibrium steady state systems, and has been called “ecological resilience” (Gunderson and Holling, 2002; Folke, 2006; Jørgensen et al., 2016). It essentially corresponds to the capacity to maintain functioning in spite of the multiple stressors which may affect an evolving system (Levin and Lubchenco, 2008). This second meaning addresses more the system’s renewal, regeneration, or re-organization after a disturbance than its recovery (Folke, 2006), which implies the assumption that disturbances and spatial heterogeneity determine the behavior of each system to be unique. As a consequence, recovery trajectories might be difficult or impossible to predict, due to the complexity of the system combined with unexpected compounded effects of disturbance, and a recovered system may eventually look identical to the previous one but is not the same system. As any other living system, it will be continuously developing (Folke, 2006; Jørgensen et al., 2016). Differences in degradation and recovery trajectories can be called system hysteresis (Elliott et al., 2007; Jørgensen et al., 2013), and in practical terms, ecological resilience can only be estimated by means of resilience proxies (Carpenter et al., 2005), which must be based on a broad resilience analysis, together with the identification of specific disturbance regimes and societal choices regarding desired ecosystem services (Brand, 2009).

What is the expected relationship between ecological resilience and critical natural capital? In simple terms, an ecosystem’s degree of ecological resilience is assumed to be inversely related to its degree of threat (Brand, 2009), and therefore holding information on ecological resilience and system efficiency constitutes a pre-requisite to assess whether an ecosystem will reach a critical state as a response to environmental stressors (Ulanowicz et al., 2009; Jørgensen et al., 2016). Thus, a critical state regarding natural capital matches an extent in environmental degradation that exceeds a threshold beyond which the current level of social welfare cannot be supported. Such an ecological criticality appears therefore to be most important for the maintenance of estuaries and coastal marine ecosystems services and goods (Jax, 2005) and the sustainable use of their natural capital (Brand, 2009).

Estuaries and coastal marine ecosystems and their modification as a

function of human stressors (e.g. overfishing or pollution) must be examined accounting to their carrying capacity and its loss next to stress. Carrying capacity is a concept originally defined as the number of individuals of a population that can be supported by a given environment without significant negative impacts to that population and that environment (Elliott et al., 2007). This definition is merely ecological and does not entirely capture the multi-layered processes of human-environment relationships, which have a fluid and non-equilibrium nature, perhaps neglecting the influence of external forces on environmental change (Moore et al., 2009). Aiming at improve the concept generality, Elliott et al. (2007) highlighted that carrying capacity must also be related to the social and economic aspects of ecosystems, looking upon which level of human activities and anthropogenic pressure can an ecosystem tolerate before undesirable changes occur. This means that it must be anticipated that humans' relationships with their environment are in principle more complex than those of other species with theirs (Pulselli et al., 2008). Actually, humans have the capacity to modify the type and degree of their impact on their environments, for instance by increasing fisheries, by using more intensive farming techniques in aquaculture, or when a defined local area is left free of productive activities, or when marine products consumption is scaled back. Humans can at the limit decrease irreversibly environment productivity and/or radically occupy or transform space. So, many species can modify the carrying capacity of their systems, but since only humans can manipulate ecosystems to such a drastic extent, the concept of carrying capacity must be expanded to include socio-economic aspects (MacLeod and Cooper, 2005; Elliott et al., 2007).

A holistic approach to understand, manipulate, and manage the environment may be provided by linking and integrating these ecological concepts and the management framework (Jørgensen et al., 2016). Ideas relating environmental management to the dynamics of ecosystems and the relations between biodiversity and ecosystem function showed particularly crucial, leading to the perspective that ecosystems are complex adaptive systems, which are characterized by their historical dependency, as well as by nonlinear dynamics, threshold effects, various basins of attraction, and limited predictability (Folke et al., 2004; Duit and Galaz, 2008; Moore et al., 2009). For instance, it has been showed that estuarine ecosystems temporal stability and biodiversity might follow different trends in relation to the systems' ecological quality status, exhibiting therefore a non-linear relationship (Pinto et al., 2013b, 2014a). According to these findings, the optimal condition with regard to estuarine stability (with higher values) might occur for average values of species richness, inducing that consequently, this may influence ecosystem services provision. Furthermore, this was confirmed through the analysis of estuarine food webs under distinct levels of eutrophication pressure, using mass-balanced models. In this case, a tendency for a decrease in food web connectivity was observed during a recovery process, from more eutrophic to less eutrophic conditions (Baeta et al., 2011), while the ecosystem's temporal stability tended to increase in the same period.

In which way can this panoply of theoretical concepts be applied to estuarine coastal environments, whose management involves so many uses and users, sectorial interests, and governance regimes (Costanza et al., 1998, 1999; McLusky and Elliott, 2004)? How can we decide, for instance for the restoration or sustainable use of a specific ecosystem, which will be the best possible course of management in a multitude of driving forces which may be conflicting? In such multiuse/multiuser/multi-sectorial systems management solutions require that we are able to orientate ourselves amongst such complexity. Marques et al. (2009) proposed the use a conceptual guidance tool – the Ecological Sustainability Trigon (EST) – which may possibly be useful as a sort of compass to provide orientation in the process of building and testing management scenarios to approach environmental problems. Although the proposal was mostly based on ideas upcoming from the marine coastal and estuarine field, they seem to be also applicable to other domains.

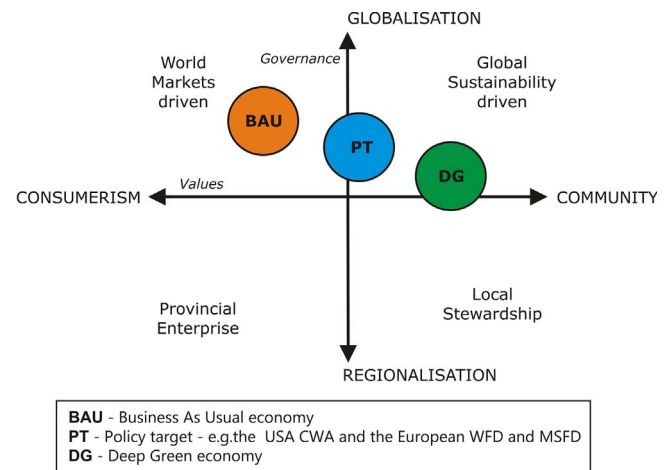


Fig. 1. Different economic scenarios resulting from supporting the natural or to the social system, as a function of political decision systems (based on Turner et al., 1994).

2. Sustainable development and ecological sustainability of estuaries and coastal areas: using EST in building management scenarios

It is generally accepted that there is an intrinsic complexity in environmental problems, and also that these are closely related to the development of human society (Jørgensen et al., 2015). As a consequence, possible solutions to environmental problems always require taking into account different points of view, often expressing the conflicting perceptions of multiple sectors, uses, and users (Costanza et al., 1998, 1999). Different economic scenarios (Fig. 1) (Turner et al., 1994, 2003; Turner, 2008) have been into a certain extent trying to address the uncertainty involved in dealing with environmental problems, and it is clear that in what way the natural or the social systems become favored will greatly depend on the different options and systems of decision (see Table 1). With regard to sustainability, environmental scenarios analysis is therefore required as a tool to recognize and characterize central questions (Table 2), as well as to take decisions about priorities and solutions (Kontogianni et al., 2001, 2004; Swart et al., 2004).

Sustainability science is therefore complex and uncertain, but it is possible to encompass all the different viewpoints and concerns in the frame of three major driving forces (Marques et al., 2009):

- The search for human well-being and the maintenance of human health and safety;
- The attempt of ecological sustainability and maintenance of natural environmental well-being;
- Systems' resilience in face of an increasing human pressure, resulting from population size and demand for wealth creation.

Certainly, it is needed to assume that research should complementary cover these three views and simultaneously fulfil the goals of creating knowledge and wealth, and improve life quality. The search for human well-being, from the governance point of view, is often endorsed as corresponding to Gross Domestic Product (GDP) or to stakeholder benefits, which could ultimately be expressed by some sorts of metrics such as well-being indices (Diener et al., 1999; Diener, 2000) (Fig. 2). The straightforward societal objective has been maximizing economic goods and services, which is usually reflected in governmental approaches, and at the same time, into a certain extent, protect ecological goods and services, at least to avoid business of being accused to harm the later ones, or to prevent countries from being subject to legal violation proceedings for not fulfilling rules settled in common legislation, as it is the case of the European Union Directives (Marques

Table 1
Environmental ideologies and sustainability perspectives (Turner et al., 2003; Turner, 2008; Marques et al., 2009).

Very weak sustainability	Weak sustainability	Strong sustainability	Very strong sustainability	
Resource exploitative, growth maximization position. Anti-green economy; Unfettered Free Markets; Widening income inequality not problematic; Free-trade in international markets.	Resource conservationist and managerial position. Green economy natural capitalism and new industrial systems green markets guided by economic incentive instruments (EIs) (e.g. pollution charges etc.) in combination with voluntary agreements. Modified economic growth (adjusted green accounting to measure GNP); Formal policy integration and review on institutional structures of growth and environmental quality.	Resource preservationist position. Deep green economy, steady state economy regulated by macro-environmental standards and supplemented by EIs and international agreements.	Extreme preservationist position. Very deep green economy, heavily regulated to minimize resource-take; National environmental duty of care formally regulated; Extensive and binding international agreements.	Green Labels
Primary economic policy objective, maximize economic growth (max Gross National Product) (GNP); No formal policy integration processes.		Zero economic growth; Zero population growth; Binding policy integration.	Reduced scale of economy and population; Sustainability accounting the primary approach.	Type of economy
Taken as axiomatic that unfettered free markets in conjunction with technical progress will ensure infinite substitution possibilities capable of mitigating all local scarcity limits constraints (environmental sources and sinks); voluntary approach to environmental regulation and intervention.	Decoupling of growth and environmental quality important but infinite substitution rejected. Sustainability Rules: e.g. constant natural capital rule; Use efficiency and productivity; Sustainability indicators and monitoring.	Decoupling plus no increase in scale; Systems perspective – health of whole ecosystems very important; over-compliance with international environmental agreements; Sustainability assessments and audits.	Scale reduction imperative; At the extreme for some there is a literal interpretation of the Gaia hypothesis with moral obligations.	Policies and management strategies
Support for traditional ethical reasoning: rights and interests of contemporary individual humans; instrumental value (e.g. recognized value to humans) in nature.	Extension of ethical reasoning: caring for others motive intergenerational and intergenerational equity (i.e. contemporary poor and future people); instrumental value in nature.	Further extension of ethical reasoning: interests of the collective take precedence over those of individual primary value of ecosystems and secondary value of component functions and services. Strong local/community awareness and action campaigns.	Acceptance of bioethics (i.e. moral rights/interests conferred on all non-human species and even the abiotic parts of the environment: Intrinsic value in nature (i.e. valuable in its own rights regardless of human experience). Cultural shifts to the maintenance of local livelihoods and environmental stewardship.	Ethics
Low level of environmental awareness in the public.	Wider public education, establishment of stakeholder groups and of e.g. roundtables to increase inclusion.			Degree of public inclusion

Table 2

Core questions for sustainability science (modified from Swart et al., 2004; Marques et al., 2009).

1. How can the dynamic interactions between nature and human society – including time-lags due to inertia – be better incorporated into emerging models and conceptualizations that integrate the global systems, human development and sustainability?
2. How are long-term trends and widely varying spatial scales in environment and development, including consumption and population change, reshaping nature-society interactions in ways relevant to sustainability?
3. What determines the vulnerability and resilience of the nature-society system in particular kinds of places and for particular types of ecosystem and human livelihoods?
4. Can scientifically meaningful limits or boundaries be defined that would provide effective warning thresholds beyond which the nature-society systems are at a significantly increased risk of serious degradation?
5. What systems of incentive structures – including markets, rules, norms, and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
6. How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to achieve sustainability?
7. How can today's relatively independent activities of research, planning, observation, assessment, and decision-support be better integrated into systems for adaptive engagement and societal learning?
8. How can future changes be determined and predicted in a creative, objective, rigorous, and policy-relevant manner that reflects sustainability and incorporates different perspectives?

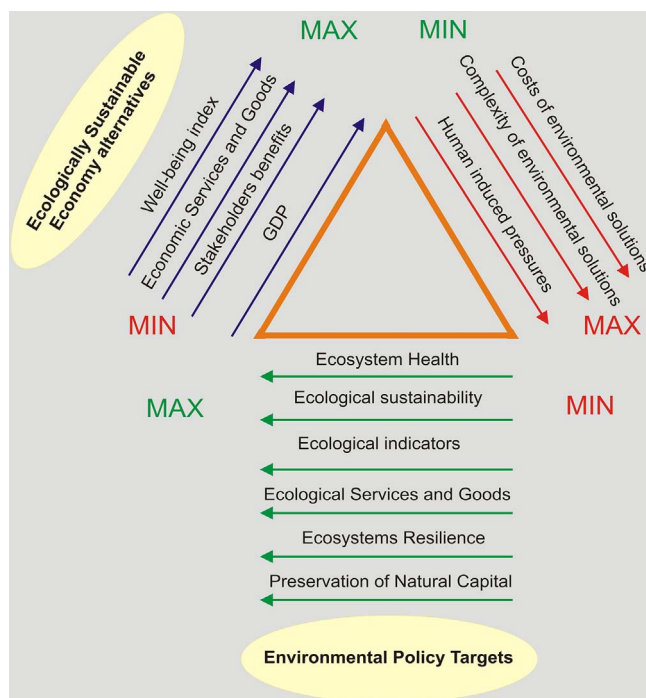


Fig. 2. The Ecological Sustainability Trigon (EST) (Marques et al., 2009) illustrating the expected trends and relationships between variables assumed to be correlated with ecological sustainability, human well-being and human induced pressures. The bottom and left-hand axes of the EST indicate how governance and societal systems must be linked to environmental management, namely through the definition of policy targets and the choice of ecologically sustainable economy alternatives, while the right-hand axis illustrates how increasing human pressures imply consequences on the other two axes. Green – Good; Red – Bad. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2009).

Sustainability indicators and composite indices have been progressively accepted as valued tools in terms of policy making and public communication with regard to environment, economy, society or technological improvement (Singh et al., 2009), as well as to human

quality of life (Diener and Tov, 2012). Nonetheless, in many cases, when applied in policy, sustainability indices appear to fail in fulfilling fundamental scientific requirements, turning them somewhat useless or even confusing for policy advice (Brunner and Starkl, 2004; Böhlinger and Jochem, 2007; Marques et al., 2009). However, despite difficulties in establishing unquestionable quantitative relations, the concept of environmental integrity is normally associated to the aim of ecological sustainability. Environmental integrity can be perceived from different theoretical orientations, all involving inherent uncertainties (Fig. 2). Panoply of tools available to evaluate environmental integrity (e.g. environmental quality indices) is vast, although probably none of those tools is entirely appropriate (Pinto et al., 2009; Marques et al., 2009). On the other hand, the value of integrated approaches has been illustrated (Pinto et al., 2014a), particularly through examples where the DPSIR (Drivers, Pressures, State Change, Impacts, Response) approach can be related to the selected indicators (McLusky and Elliott, 2004; Aubry and Elliott, 2006; Borja et al., 2008; Gray and Elliott, 2009; Pinto et al., 2013b). Furthermore, a new interest in defining, measuring and protecting ecosystem goods and services developed from the acknowledgement that economic prosperity depends on ecosystem functioning and that many natural ecosystems are threatened (Pinto et al., 2010).

Independently from such recognition regarding the importance of ecosystem services and goods, there are two main problems in assessing them, which are: i) certain functions do not become important always at the same scale ((Heal and Kristrom, 2005); and ii) the integration and aggregation of all temporal and spatial scales information may originate problems due to the fact that interrelations and feedback loops may operate at scales above the level being assessed (Pinto et al., 2010). A good illustration of this, in highly dynamic estuarine, coastal and marine areas, is the dependency of economic goods and services at one area from the successful functioning somewhere else. For instance, estuarine fish nursery grounds in one area create the conditions for the existence of marine commercial stocks in another area (McLusky and Elliott, 2004; Pinto et al., 2010). As a consequence, scaling rules attempting to describe ecosystem services provision and delivery, especially for open and dynamic systems, still require to be quantified and defined (Limburg et al., 2002), which is particularly evident regarding estuarine and coastal ecosystems (Pinto et al., 2013a, 2014a).

The human population pressure is increasing as a consequence of population growth and the associated higher resource consumption and pollution related to the pursuit of satiating cumulative human needs. The complexity, difficulty, and intrinsic costs of solutions necessary to deal with environmental problems created by such pressure have been increasing gradually (Fig. 2). There is no reason to think that the needs of future generations will be different from ours in terms of quantity and quality, and therefore we may anticipate that two changes might happen as compared to today: (i) decrease in global carrying capacity, and (ii) decrease in the number of choices available, meaning by this both the number of different resources and our capacity to exploit them. Possibly, both in terrestrial and aquatic ecosystems, shifts in regimes in relation to resilience and the functional roles of biological diversity will occur (Folke et al., 2004; Pinto et al., 2014a), and eventually future generations may have to adapt rapidly their ways in accordance to ecosystems sustainable management (Pinto et al., 2014b).

We assume here that ecological sustainability constitutes a major goal for human society, which reflects in international agreements adopted by most countries (e.g. the Convention on Biological Diversity) and national laws approved. Nevertheless, at the present levels of human population size and associated environmental pressure, it is not conceptually possible to maximize at the same time ecological sustainability and stakeholder benefits. Still conceptually, it would eventually be possible to maximize ecological sustainability in a situation of extremely large human population size, but this would entail considerably low standards of human well-being. Of course, in the short term, we may consider maximize stakeholders' benefits and environmental anthropogenic pressures, but only if we renounce to the goal of

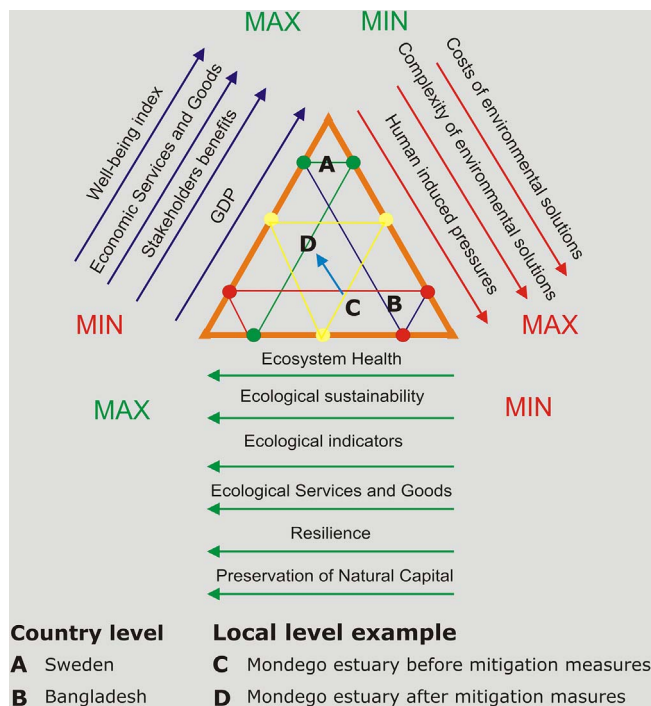


Fig. 3. Proposed use of the Ecological Sustainability Trigon in building and analysing management scenarios: Analysis of the expected variations and relationships of different indicators and variables correlated with ecological sustainability, human well-being and human induced pressures (see legend of Fig. 2 for details). Green — Best scenario; Red — Worst scenario; Yellow — Acceptable scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ecological sustainability, compromising the future in the longer run. It seems clear that in this “game of possibilities” there is no conceivable scenario that allows maximizing the simultaneously ecologically sustainable solutions for human development, the search for human well-being, and environmental human driven pressures, although a trade-off between the three might be conceptually possible. Marques et al. (2009) called such trade-off the “ecological sustainability trigon” (EST) (Fig. 3), in which the bottom and left-hand axes indicate how governance and societal systems must be linked to environmental management in order to increase the chances of moving both from MIN in the direction of MAX, which constitutes the goal. The right-hand axis illustrates how increasing human pressures from MIN (best scenario) towards MAX (worst scenario) inevitably conditions the other two axes determining adverse consequences.

Different issues under discussion (indicators, objectives, pressures etc.) can be arranged along the EST corresponding axis, which allows an immediate and intuitive rough integrated view of conceivable implications of policy or management decisions, even when processes behind relationships are not completely understood, as it is often the case in estuarine and coastal ecosystems. Furthermore, while relationships are assumed to be non-linear, all imaginable case studies roughly correspond to a position on the EST frame. At the country scale, Sweden for instance — a small, rich population, with good coastal ecosystem governance, few environmental problems and a high capability to tackle those problems — would be placed approximately in position A (Fig. 3). On the other hand, Bangladesh, including the Sunderbans mangrove area, which have a large population and high human stress, poor funding and badly structured governance systems to implement resolutions, large pressures on ecosystems, and solutions almost ecologically insensible, which distresses its population well-being, could come approximately to position B. At the local scale, as a result of the application of some mitigation and recovery measures aiming at dealing with eutrophication problems, the Mondego Estuary, on the western coast of Portugal, showed an improvement in its ecological

quality condition during the last decade, and a positive evolution of regulation and cultural ecosystem services, concomitant into a certain extent to an increase in stakeholders’ benefits (Pinto et al., 2013b, 2014a). This corresponded roughly to a gradual evolution from position C to position D since the mid1990s up to present (Fig. 3).

The two classic examples at the country scale plus the third one at the local scale, illustrate how the EST may help decision makers a) in identifying the links between drivers and b) in clarifying/deciding about the best management options in order to convey any system closer to an optimal condition in the trigon. Independently from the scale of the management scenario we may want to build, the EST might in principle be used as a conceptual guidance tool, which constitutes one of its most interesting features.

Obviously, we must accept that certain things can be managed and other things cannot, and consequently choices have to be made. It is with regard to such choices that the EST may constitute a useful intuitive tool. Bangladesh, for instance, at least in the short term, cannot alter its population size and concomitant human pressure, but governance and environmental management could eventually be improved. Similarly, at a local scale environmental management, some pressures can be handled, like for instance in the Mondego Estuary, where mitigation measures included altering the discharge of point-source polluting materials, allowing decrease eutrophication symptoms in estuarine areas, although the general eutrophic situation in the river basin could not be yet be solved (Veríssimo et al., 2013).

Climate change, as an ‘exogenic unmanaged pressure’, is an example of something which cannot be managed. In fact, far from managing it, local managers can only respond to its consequences. It will have a foreseeable impact on ecosystems in general and on the human society, and eventually will impede possible ways to achieve sustainable development.

Regarding coastal zones, the most evident threats related to climate change are rising temperatures and the related global rise in sea level, reflected in increased coastal erosion and retreat, inundation and eventual submersion of low-lying coastal areas (Harvey and Nicholls, 2008; Moss et al., 2010). Such changes will mostly affect areas within 60–200 Km to the shoreline, which include tidal-flats, coastal flood-plains, mangroves, saltmarshes etc., where a large share of the human population is concentrated (something like half, with an increasing trend), as well as improved transportation systems, technological services, industries, major cities, tourism activities and food production (Yohe and Tol, 2008; Hanson et al., 2011).

Even without considering climate change, interactions within and between the natural and human systems are particularly strong in coastal zones, leading to coastal ecosystems degradation, and consequently to severe negative implications for the well-being of societies that depend on coastal ecosystems goods and services. But in management scenarios, to these manageable threats, we must add the non-manageable probable climate-related changes to which we can only respond through adaptation:

- More frequent and strong extreme events, such as heat or cold waves (Albrecht et al., 2009);
- A sea level rise, gradually faster, of 20–60 cm or more by the end of the century (Schaeffer et al., 2012; Sriver et al., 2012);
- Increase in sea surface temperatures (1–3° C), which will impact corals, possibly causing its extensive mortality (Flannery, 2005);
- Ocean acidification due to water uptake of CO₂ from the atmosphere, which also impact corals and other calcareous organisms, and probably primary productivity (Flannery, 2005);
- More intense cyclones and storms in tropical extra-tropical areas (von Storch and Worth, 2008);
- Changes in precipitation/run-off (Gardner, 2009).

The Impacts of such climate-related changes will be felt essentially of two types: a) sectoral, affecting different natural systems, as well as

human systems and activities, and b) regional, which refers to the ability of different geographic regions, with different natural and socio-economic characteristics, to face changing climatic conditions.

Eventually, water pollution, global warming, and sea level rise will be the origin of sectoral impacts such as water scarcity, increased number of droughts and floods, more frequent cyclones, water related diseases, threats to crops, and losses in biodiversity, while sea level rise, by submerging coastal low-lying areas and small islands, will threaten settlements and industrial facilities.

The way such changes may worsen the living conditions in general in each geographic region, affecting the day-to-day socio-economic development, will obviously be different from continent to continent, but threats and uncertainty regarding building environmental management will be global.

In general, it must be accepted that solving the increasing complexity of environmental problems cannot be the only condition to reconcile the difficulties in accounting for the three driving forces simultaneously (achieve and keep ecological sustainability human well-being goal, and dealing with human population/size pressure). Indeed, the benefits from pursuing a possible harmonization by implementing complex solutions will not increase linearly as a function of that complexity, as the intrinsic costs (energy and money) will plausibly become unsustainable in the long run (Fig. 4).

3. What might be the advantages of using the ecological sustainability trigon (EST)?

The ecological sustainability trigon (EST) proposal (Marques et al., 2009) represented a tentative and intuitive view which has been requiring further testing and debate (Pinto et al., 2013a, 2014a, 2014b). In fact, the number of variables that must be taken into account when building management scenarios is often very high, as well as the uncertainties regarding their relationships and trends. The core problem resides in understanding into what extent interactions between given economic and ecological systems are sustainable, which involves cross-scale, transcultural, and transdisciplinary fundamental questions, calling for innovative approaches in research, in policy, and to build social institutions (Costanza et al., 1998; Costanza et al., 1999; Jørgensen et al., 2015). EST as a conceptual framework has been tested with interesting results at local level case studies (Pinto et al., 2013a, 2014a), as a kind of compass to provide orientation in building estuarine management scenarios (“In which direction do we want to go?” “How do we get there?”), alternatively to more conservative forecast scenarios (“Where are we going to?”). In fact, besides addressing

adaptations to current conditions and actions to be undertaken in the short term, management scenarios should also be built to accomplish transformations towards more sustainable development pathways (Folke, 2006).

As shown in Figs. 2–4, different variables whose tendencies of variation are in principle correlated can be arranged along the corresponding sides of the triangle, with their expected trends varying from Maximum (MAX) to Minimum (MIN). Examples of variables are provided, but many other could of course be included, which may prove particularly useful namely when policy targeted approaches are pursued in exploring ecosystems’ resources (e.g. implementing the European Water Framework Directive, or the European Marine Strategy Framework Directive) (Pinto et al., 2014b).

For instance, applying governance theory, which accounts for the legal and administrative aspects of policy implementation, implies establishing hypothesis on how different governance forms can be expected to handle processes of change, which are characterized by nonlinear dynamics, threshold effects, and cascades, being therefore poorly predictable (Duit and Galaz, 2008). Also, perhaps due to scientific uncertainty and to lack of consensus among scientists, linkages between ecological science and environmental policy are poor, which jeopardizes the transfer of science into management (Moore et al., 2009; Pinto et al., 2010; Borja et al., 2011). The usefulness of the EST as an orientation tool may possibly be further explored in testing governance hypothesis. Moreover, EST can also be tested in analysing and integrating, at least approximately (especially as correlations are far from being linear), the expected variations and interactions between different variables assumed to be correlated with ecological sustainability, human well-being and anthropogenic pressures. Namely for decision makers, these possibilities represent a great potential with regard to an intuitive clarification of what might be compliant and what is probably not compliant with the goal of sustainability, as well as in establishing possible safety margins in the “game of possibilities”.

One of the advantages of the EST approach is being able to address and measure the different environmental components with a same species-specific currency, i.e., the human society view and, at the same time, of describing at the light of ecological theory and systems’ ecology (Jørgensen and Müller, 2000) our behavior, energetics (economy), and dynamics. More than ever, the incorporation of our behavior, energetics, and dynamics into an ecosystem integrity framework represents a crucial challenge for the science of ecology, which requires measures of ecological status from the ecosystem organization and functioning points of view, rather than from pressures and vulnerability. Nevertheless, the EST approach allows making the evaluation

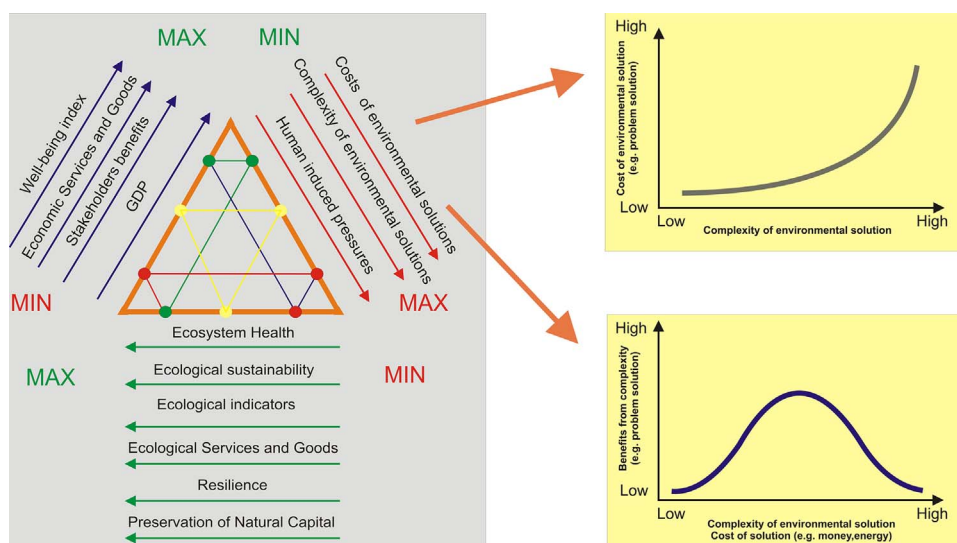


Fig. 4. Proposed use of the Ecological Sustainability Trigon in building management scenarios: Expected trend in costs and benefits as a function of an increasing complexity of environmental problems solutions, namely to meet policy targets, forces the adoption of environmentally viable economic activities.

criteria for environmental management scenarios more explicit, meaning that scales should match (time and space), interactions should match (relationships), and rates should match (biophysical limits), constituting therefore a promising tool for gap analysis (information concerning knowledge lacunae), as well as to address new research questions.

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